

A Compact Array Antenna: Explicit Design for C and X Band Applications

Saeed MOHAMMADI-ASL¹, Javad NOURINIA¹, Changiz GHOBADI¹, Maryam MAJIDZADEH²

¹ Electrical Engineering Dept., Urmia University, Urmia, Iran

² Electrical Engineering Dept., Urmia Technical College, Technical and Vocational University, Urmia, Iran

asselectco@gmail.com, j.nourinia@urmia.ac.ir, ch.ghobadi@urmia.ac.ir, m.majidzadeh@tvu.ac.ir

Submitted January 3, 2017 / Accepted May 17, 2017

Abstract. A novel and compact design of a circularly polarized slot antenna (CPSA) is elaborated. With the aim of generating CP feature and enhancing the impedance bandwidth, four rectangular stubs are wisely embedded in the antenna feed line structure and slotted ground plane to excite two orthogonal E vectors. Subsequently, a suitable arrangement of CPSAs in the form of 2×2 and 4×4 array antennas provokes higher functionalities in C and X band applications, respectively. Sequentially rotated (SR) feed technique is adopted to excite the antenna structure in array configurations. Measured and simulated results confirm outperformance of the array antennas with respect to the previously proposed designs. Compact size, wider impedance and axial ratio (AR) bandwidth, higher gain, and suitable radiation characteristics, both in single and array configurations, confirm suitability of the proposed designs for communication systems.

Keywords

Circular polarization (CP), C and X band applications, sequential rotated (SR) feed network, array antenna, high gain

1. Introduction

Circular polarization (CP) antennas exhibit marvelous merits over their linearly polarized (LP) counterparts. Among them are the ability to overcome multipath fading problem, performance independency to the path between transmitter and receiver, and the ability of withstanding against unsuitable weather conditions. The CP characteristic is usually obtained by exciting two orthogonal electric field vectors in phase quadrature. To do so, different CP generation techniques have been investigated in the literature [1–4]. Each of these techniques is shown to be effectively deployed in the desired operating band. More recently in an attempt to achieve high-performance designs, the notion of antenna arrays is developed and further improved [5]. The key to this triumph is the provision of

salient technical features including higher gain, improved performance, and suitable radiation properties. Specifically speaking, an array antenna is composed of a number of single antennas being arranged in a specific manner. The target is to attain better performance rather than the constituting single antenna structures. In this context, effective designs with dedicated functionalities are proposed. To extend the desired functionalities, CP arrays have also been proposed as prominent alternatives due to combination of both CP and array features concurrently [6], [7]. Each of these studies puts forward an effective sketch of CP array with its corresponding characteristics. Although these studies have contributed to enhanced performance in both technical and structural metrics, further improvements could be still pursued.

Contemplating on the aforementioned subject, this manuscript outlines a novel structure of a CP slot antenna (CPSA). The antenna configuration is composed of a simple slotted ground plane and a rectangular feed line. Four rectangular stubs, two in the ground plane and two other on the feed line, are wisely embedded in the antenna body to both enhancing the operating bandwidth as well as generating CP characteristics. The proposed design is simple, compact, and cost effective with broad band 10 dB impedance and 3 dB AR bandwidth. Then, with the aim of benefiting from both CP and array properties, the aforementioned CPSA is utilized as the constituting elements of a 2×2 and 4×4 slot array antennas (SAA). These SAA structures are printed on FR4 substrate with thickness of 1 mm and loss tangent of 0.02. Sequentially rotated (SR) technique is adopted to design the feed network in the array configurations. However, in most of the conventional designs, T junctions are utilized in the feed networks which suffer from undesired radiation in the connecting points [8], [9]. To provide adequate numerical validations, 2×2 and 4×4 SAAs are implemented in Ansoft High Frequency Simulator (HFSS) version 15. Besides the simulation studies, experimental prototypes of these SAAs are measured in the antenna and microwave laboratory. This task assists in confirming applicability of the proposed designs in real-world applications. To make it brief, the main contributions of the present study could be listed as follows:

- Devising a novel scheme of a compact CP slot antenna in consistent with techno-economic objectives.
- Settling the proposed design in 2×2 and 4×4 arrangements to contribute to a smaller sized SAA with wider impedance and axial ratio (AR) bandwidth along with higher gain values against the similar structures.
- Implementation of SR feed network to further improve the CP feature and enhancing performance of the proposed SAA.

These features are well-supported throughout the study. This manuscript continues as follows: Section 2 discusses the single CPSA design process. Bandwidth and AR enhancement procedures are discussed in detail, too. Section 3 addresses the proposed SR feed network. In Sec. 4, a 2×2 SAA is formed, based on the proposed CPSAs and the established SR feed network. Section 5 includes a similar analysis conducted on 4×4 SAA with 16 single CPSAs. Both of 2×2 and 4×4 SAAs are investigated in more details. Section 6 includes a comparative study between the proposed and the archived designs to interrogate the promising merits. Ultimately, Section 7 concludes the manuscript.

2. CPSA Design

The proposed CPSA design is illustrated in Fig. 1. As it is shown, the main body of the antenna is composed of a simple slotted ground plane along with a rectangular feed line. To enhance the impedance bandwidth and generate CP characteristics, two stubs are embedded in the slotted ground plane. Moreover, two other stubs are supplemented to the feed line to further enhance the antenna performance. This antenna is printed on commercial FR4 substrate with the thickness of 1 mm and loss tangent of 0.02. The antenna size is $20 \times 20 \times 1$ mm³ which is smaller than the similar CP antennas, archived recently. Detailed values of the aforementioned CPSA are listed in Tab. 1.

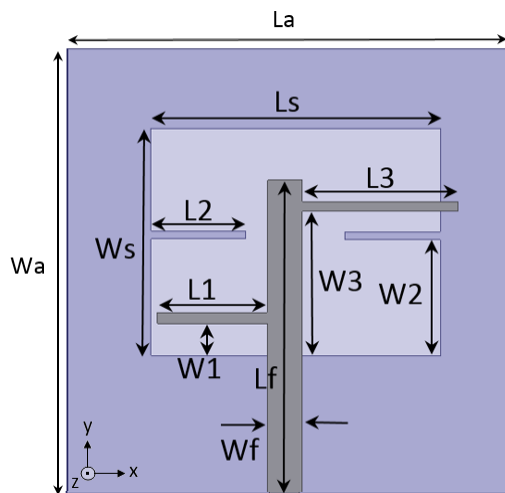


Fig. 1. Configuration of the proposed CPSA.

Parameter	Value (mm)	Parameter	Value(mm)
L_a	20	L_1	5.9
W_a	20	W_1	0.8
L_s	15.2	L_2	4.9
W_s	11	W_2	5.2
L_f	14.3	L_3	8.2
W_f	1.8	W_3	6.7

Tab. 1. Detailed values of CPSA parameters.

2.1 CPSA Design

To provide a fruitful investigation on the proposed CPSA, the design process is investigated in three different steps, shown in Fig. 2. In step 1, a slotted ground plane and a simple rectangular feed line is adopted in the antenna body. In step 2, two rectangular stubs are supplemented to the feed line. Finally, in step 3, the final configuration of CPSA is achieved within which two extra rectangular stubs are added to the slotted ground plane. All the three aforementioned structures in steps 1, 2, and 3 are simulated using Ansoft High Frequency Structure Simulator (HFSS) version 15. Corresponding S_{11} and AR curves are extracted in Figs. 3a), b), and c), respectively. As can be seen, in step 1, narrow impedance bandwidth of 4.22–4.75 GHz is covered. However, no circular polarization is obtained. In the next step, say step 2, a judicial inclusion of two rectangular stubs in the feed line structure improves its impedance bandwidth. Thus, 5.43–6.97 GHz band is covered. Still, 3 dB AR bandwidth is not granted. In the final step, when the rectangular stubs are also included in the slotted ground plane, both impedance and AR bandwidths are enhanced greatly. It can be evidently recognized that CP feature is generated when two orthogonal E vectors are excited. To this end, suitable paths should be perceived to let the surface current to flow through them and excite orthogonal vectors. Herein, inclusion of stubs in the antenna structure, ends in formation of perpendicular current

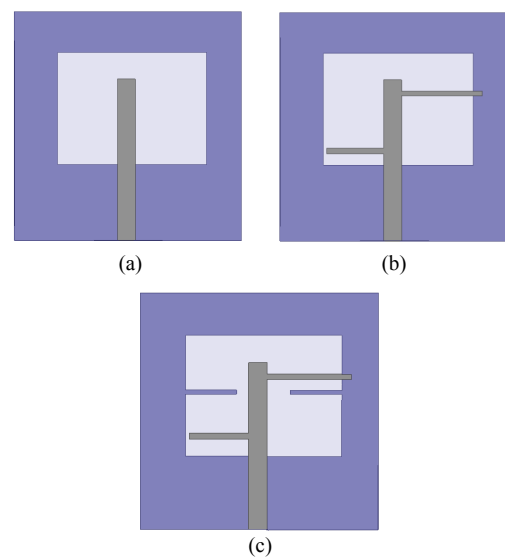


Fig. 2. Design steps of the proposed CPSA: (a) step 1, (b) step 2, and (c) step 3.

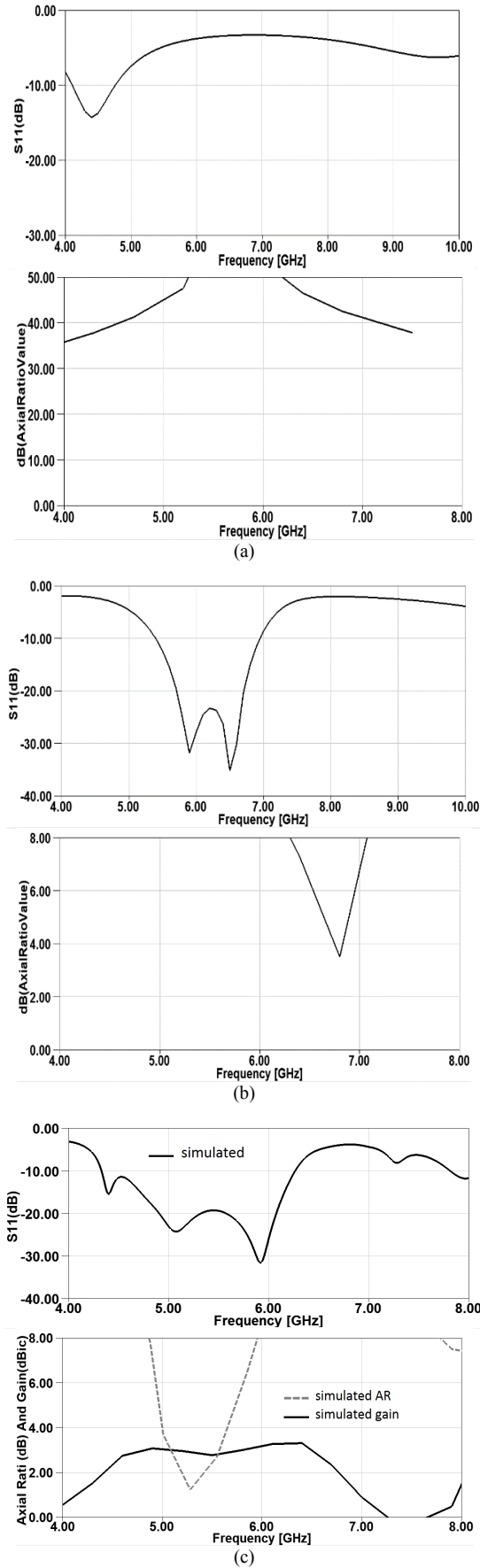


Fig. 3. 10 dB impedance bandwidth and 3 dB AR bandwidth: (a) step 1, (b) step 2, (c) step 3.

paths in which surface current circulates and results in CP generation. The obtained results indicate that the proposed CPSA operates over the frequency range of 4.33–6.37 GHz for $S_{11} < -10$ dB. Simultaneously, AR bandwidth covers 5.14–5.58 GHz. The antenna gain is also depicted in Fig. 3c). It can be easily seen that the gain values are around 3 dB over the operating CP frequency band.

3. SAA Feed Network Structure

Feeding strategy of an antenna structure demonstrates a prominent impact on its overall performance. Due to ease of implementation, a simple feed line is generally deployed to excite the antenna. This is why accurate design of feed line could yield in sensible improvements. As the antenna structures become more complex, extra efforts should be devoted to design appropriate feeding networks. This issue plays more sound in the case of array antennas. Inclusion of thousands of single antenna elements in array antenna design calls the need for an accurate and efficient feed network to achieve desired results. To this end, many techniques are provoked to feed the antenna arrays. Among them, SR technique is a popular one to obtain improved CP mechanism. The inclusion of SR feeding technology in CP array antennas yields in polarization purity increment, impedance matching, and pattern symmetry [10]. Accordingly, SR feeding technique is deployed here to attain enhanced performance of the proposed SAA. The proposed compact SR feed technique could be applied to $2^N \times 2^N$ feeding networks, which is suitable for large CPSAAs. Interested readers are referred to [11] to access detailed information on design process of SR feed network.

4. On Design and Performance of 2×2 SAA Configuration

The proposed design of CPSAs is arranged in array topologies to end in a SAA configuration. Figure 4a) shows the established design founded on 1 mm thick FR4 substrate. As well, the fabricated prototype is shown in Fig. 4b). As can be seen, four CPSAs along with a SR feed network are adopted to form the proposed SAA. As mentioned earlier, SR feed network yields in performance enhancement of CPAAs. In the investigated design, values of feeding structure parameters are reported in Tab. 2. The resultant time-varying surface current distribution on the aforementioned 2×2 SAA at 5.6 GHz is shown in Fig. 5a). As can be seen, 5.6 GHz is the minimum point in 3 dB AR bandwidth. Moreover, it can be easily captured that current distributions in 180 and 270 degrees are equal in magnitude but opposite in phase with those of 0 and 90 degrees, respectively. A fine attention on the obtained results reveals that the proposed 2×2 SAA exhibits right-hand circular polarization (RHCP) in $+z$ direction while left-hand circular polarization (LHCP) is provided in $-z$ direction.

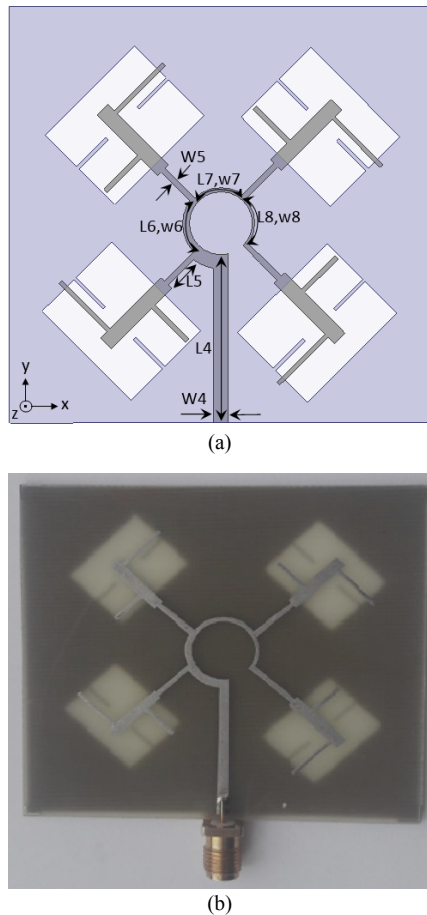


Fig. 4. (a) Schematic structure of the proposed 2×2 array antenna structure, and (b) the fabricated prototype.

Parameter	Value (mm)	Parameter	Value (mm)
L_4	0.85	W_6	1.41
W_4	20.35	L_7	6.5
L_5	3.5	W_7	1.41
W_5	2.6	L_8	6.5
L_6	6.5	W_8	1

Tab. 2. Detailed values of feeding structure parameters.

As mentioned earlier, inclusion of the stubs in the antenna body yields in impedance and AR bandwidth enhancement. Surface current distribution analysis could be pursued to confirm such functionality. Fig. 5b) displays the obtained surface current distribution on 2×2 array antenna without any stubs elements. Simulation results confirm that in 0, 90, 180, and 270 degrees, there are no current circulations and consequently, no CP is obtained. This is due to the fact that in the case of excluding stub elements, no suitable path is formed for current circulation. Accordingly, CP feature is not provoked.

The fabricated prototype is tailored to evaluate performance of the proposed SAA in real-world applications. To do so, the established prototype is measured in antenna and microwave laboratory. Figure 6a) demonstrates simulated and measured S_{11} curves for SAA structure. The obtained results approve coverage of frequency band (3.35 to 9.51) GHz by the proposed SAA. Besides, there is a close agreement between the simulated and measured results

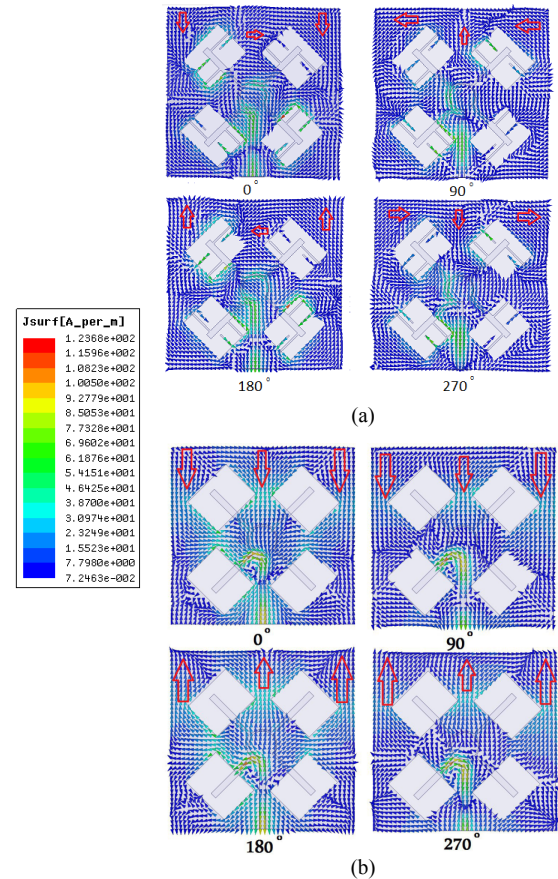


Fig. 5. Surface current distribution on 2×2 array antenna structure: (a) with rectangular stubs, (b) without rectangular stubs.

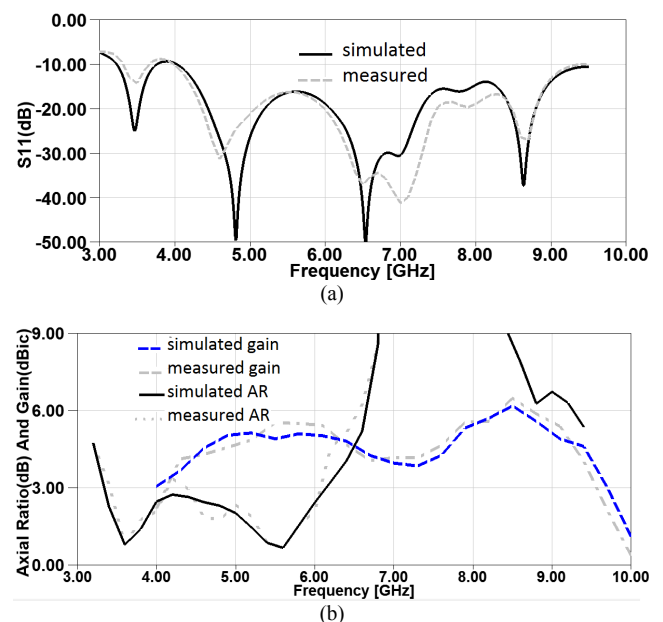


Fig. 6. (a) Impedance bandwidth, and (b) AR and gain of the proposed 2×2 array antenna structure.

confirming a dependable performance of the established design. Investigating the S_{11} curves regarding CPSA and 2×2 array antenna reveals that more resonances are excited in the case of array structure. This is due to the for-

mation of longer paths for surface current circulation on the antenna body. By taking longer paths, more resonances are excited and wider bandwidth is obtained. Figure 6b) includes simulated and measured results for AR and gain values of investigated SAA. It is evident that CP feature is achieved in the frequency range of 3.36–6.15 GHz which is thoroughly covered by S_{11} bandwidth. Moreover, the gain value is varied between 3 to 6 dB which satisfies the requirements of communication applications. Similarly, the obtained results are in consistency with their measured counterparts. An increase in gain values is recorded due to inherent characteristics of array antennas compared to that of CPSA.

5. On Design and Performance of 4×4 SAA Configuration

To end in further improvements and better results, the proposed SAA is extended to 4×4 configuration in which the constituting elements are the proposed CPSAs. Figures 7a) and b) display the schematic and fabricated configurations, respectively. As can be seen, 16 CPSAs are arranged in the form of four 2×2 SAAs. SR feeding mechanism is also adopted to excite the SAA configuration. With respect to measured and simulated S_{11} curves (Fig. 8a) it can be noticed that more resonances and wider impedance bandwidth are

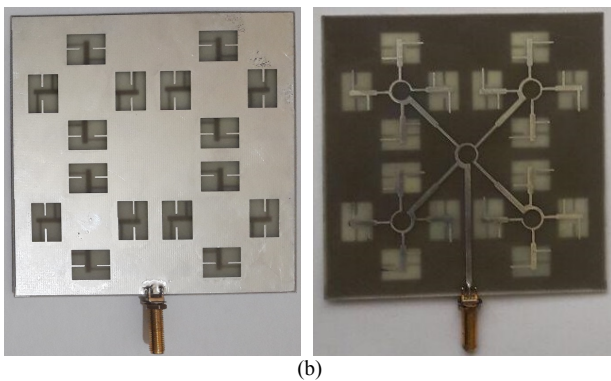
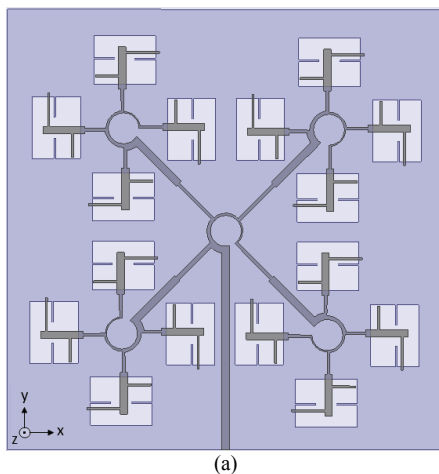


Fig. 7. (a) Schematic structure of the proposed 4×4 array antenna structure, and (b) the fabricated prototype from top and bottom view.

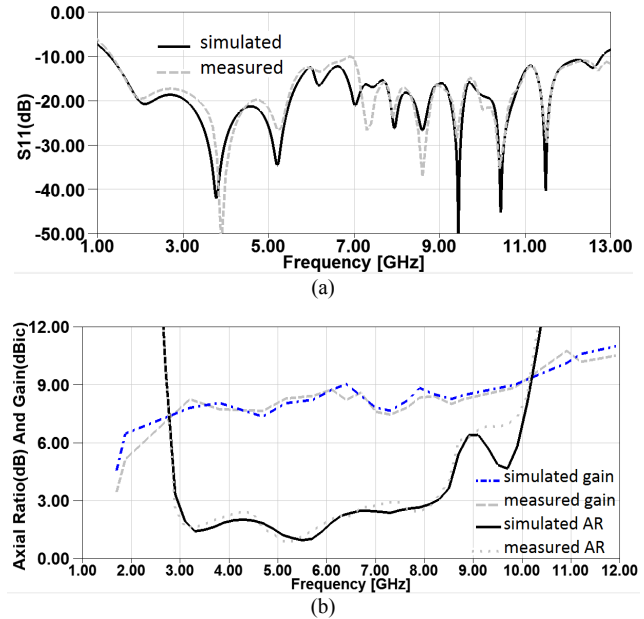


Fig. 8. (a) Impedance bandwidth, and (b) AR and gain of the proposed 4×4 array antenna structure.

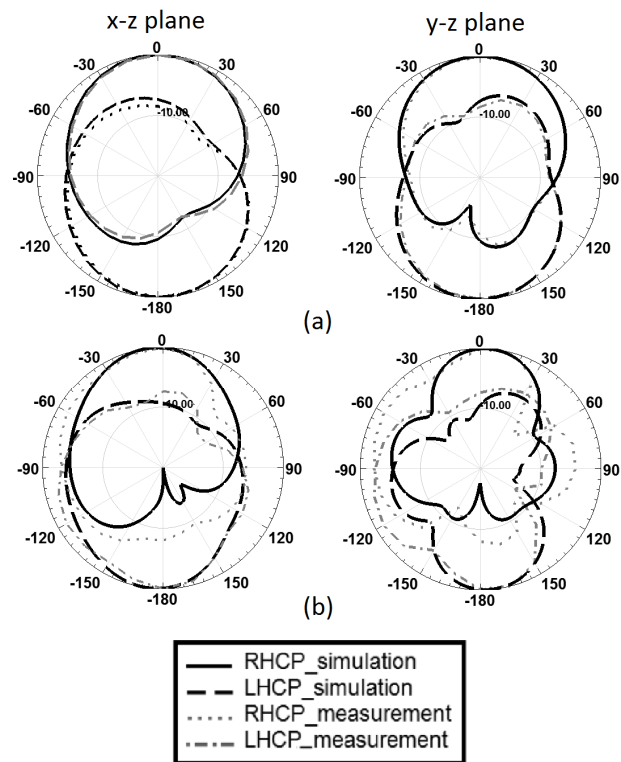


Fig. 9. Simulated and measured radiation patterns of 4×4 SAA at (a) 4.8 GHz, and (b) 6.5 GHz.

attained against the preceding 2×2 configuration. This figure signifies frequency coverage of 1.48–12.88 GHz broadening the impedance bandwidth of the established SAA. Owing to structural extensions in the form of 4×4 configuration, Figure 8b) reveals that AR bandwidth gets considerable improvement and covers 3–8 GHz frequency band. As it is expected, gain is increased by an increase in the array size. This issue could be validated based on the results in Fig. 8b). As can be seen, gain values are varied between 7

and 9 dB in the AR frequency range. Apart from this, RHCP and LHCP radiation patterns are investigated in Fig. 9 at 4.8 and 6.5 GHz. It is clearly seen that radiation patterns meet the requirements of communication systems in both xz and yz planes. As well, a proper similarity is seen between the simulated and measured results. Based on the reflected results, the proposed design is recognized as a suitable choice for C and X band applications.

Based on the conducted studies on single antenna element, 2×2 , and 4×4 array antennas, it could be deduced that array structures improve the anticipated functionalities compared to that of CPSA element. Similar conclusions are attained in regard of impedance bandwidth and AR. As well, results confirm that the obtained improvements based on 4×4 array antenna prevails 2×2 array performance in terms of wider bandwidth and increased AR. As mentioned, arranging the CPSA elements in the form of array structures provides more paths for current circulation and hence, the reflected remarks are emanated. As current takes longer paths on the antenna structure, more resonances are excited in impedance and AR bandwidth and hence, wider bandwidths are obtained.

6. Comparative Studies: The Proposed Design versus the Archived Topologies

A detailed comparative study is launched here to investigate the proposed SAA performance. To this end, the established 2×2 structure is tailored against the recently published 2×2 designs [12–17]. The comparison is conducted in terms of 10-dB impedance bandwidth, 3-dB AR bandwidth, and the total size of the array antenna. Results are reported in Tab. 3. As this table unveils, the array size in [12–16] is larger than the proposed SAA. This is while; 10-dB impedance bandwidth and 3-dB AR bandwidths are narrower which reveals a performance defect against the larger implementation space. The array antenna structure in [17] is relatively smaller than the proposed structure. However, it merely covers 29% impedance bandwidth and

15.5% AR bandwidth of the proposed configuration. The limited operating features of the investigated design do not end in lukewarm reception in the related applications. It is clearly shown that the presented SAA offers smaller size with respect to many of the previous designs. More interestingly, it exhibits better performance regarding impedance and AR bandwidths. Regarding peak gain values, 6 dBic is recorded for the proposed design. Accordingly, gain requirement of real-case communication systems is satisfied. The recorded gain value is a bit smaller than the recorded values in [12–17]. It is worth noting that higher gains are obtained via larger array structures with limited impedance bandwidth and narrower AR. However, a suitable compromise could be established to reach to a well-dressed design with anticipated functionalities. As well, comparison of radiation patterns in [12–17] reveals that suitable radiation patterns are obtained for communication systems applications in the aforementioned designs.

7. Conclusion

This study intended to propose a novel scheme of a CPSA as well as its extensions to 2×2 and 4×4 SAAs for C and X band applications. First, a CPSA with a simple and compact configuration was proposed as the array element. Then, with the aim of performance enhancement, 2×2 and 4×4 SAAs were extended. Wise combination of array elements as well as SR feed technique yielded in 10-dB impedance and 3-dB AR bandwidths enhancement. The overall size of the single CPSA, 2×2 , and 4×4 SAAs are $20 \times 20 \times 1 \text{ mm}^3$, $51 \times 50 \times 1 \text{ mm}^3$, and $107 \times 107 \times 1 \text{ mm}^3$ respectively. Comparison of the present 2×2 SAA with previous designs revealed that although the SAA in this work occupies smaller area, it provides better operating metrics. The presented SAA structures exhibit smaller size, cost effective fabrication, high gain values, and suitable performance against the recently achieved designs. As well, a close agreement was noticed between the measured and simulated results nominating the proposed design as a suitable choice for communication systems.

Comparison Term	References						
	[12]	[13]	[14]	[15]	[16]	[17]	This work
10-dB impedance bandwidth [GHz]	4–8.1	4.82–5.12	5.20–6.23	1.15–1.95	4.46–5.5	5–6.75	3.35–9.51
3-dB AR bandwidth [GHz]	4.75–6.82	4.84–5.13	5.25–5.95	1.15–1.9	4.52–5.4	5.32–6.22	3.36–6.15
Total size [mm ³]	$90 \times 90 \times 0.8$	$100 \times 100 \times 3$	$75 \times 75 \times 1.5$	$220 \times 220 \times 1.6$	$90 \times 90 \times 0.5$	$45 \times 45 \times 1.6$	$51 \times 50 \times 1$

Tab. 3. Comparison results between the present 2×2 array antenna and previous designs.

References

- [1] MOHAMMADI, S., NOURINIA, J., GHOBADI, C., et al. Compact broadband circularly polarized slot antenna using two linked elliptical slots for C-band applications. *IEEE Antennas and Wireless Propagation Letters*, 2013, vol. 12, p. 1094–1097. DOI: 10.1109/LAWP.2013.2280457
- [2] TANG, H., WANG, K., WU, R., et al. Compact broadband CP monopole antenna with tilted branch. *Electronics Letters*, 2016, vol. 52, no. 21, p. 1739–1740. DOI: 10.1049/el.2016.2733
- [3] CAO, Y.F., CHEUNG, S.W., YUK, T.I. Dual-cap mushroom-like metasurface used in CP reconfigurable monopole antenna for performance enhancement. *IEEE Transactions on Antennas and Propagation*, 2015, vol. 63, no. 12, p. 5949–5955. DOI: 10.1109/TAP.2015.2489682
- [4] SUNG, Y. Stub-loaded square-ring antenna for circular polarization applications. *Journal of Electromagnetic Waves and Applications*, 2016, vol. 30, p. 1465–1473. DOI: 10.1080/09205071.2016.1202788
- [5] BABAKHANI, B., SHARMA, S.K., LABADIE, N.R. A frequency agile microstrip patch phased array antenna with polarization reconfiguration. *IEEE Transactions on Antennas and Propagation*, 2016, vol. 64, no. 10, p. 4316–4327. DOI: 10.1109/TAP.2016.2598156
- [6] KALIS, A., ANTONAKOPOULOS, T., SORAS, C., et al. A switched dual antenna array for mobile computing network. *International Journal of Electronics*, 2002, vol. 89, no. 4, p. 325 to 335. DOI: 10.1080/00207210210126989
- [7] ZONG, B.F., WANG, G.M., ZENG, H.Y., et al. SCRLH-TL based sequential rotation feed network for broadband circularly polarized antenna array. *Radioengineering*, 2016, vol. 25, no. 1, p. 81–88. DOI: 10.13164/re.2016.0081
- [8] LI, T., DOU, W.B. Millimetre-wave slotted array antenna based on double-layer substrate integrated waveguide. *IET Microwaves, Antennas and Propagation*, 2015, vol. 9, no. 9, p. 882–888. DOI: 10.1049/iet-map.2014.0571
- [9] YEUNG, S.H., GARCIA-LAMPEREZ, A., SARKAR, K., et al. Comparison of the performance between a parasitically coupled and a direct coupled feed for a microstrip antenna array. *IEEE Transactions on Antennas and Propagation*, 2014, vol. 62, no. 5, p. 2813–2818. DOI: 10.1109/TAP.2014.2303823
- [10] LIN, S.K., LIN, Y.C. A compact sequential-phase feed using uniform transmission lines for circularly polarized sequential-rotation arrays. *IEEE Transactions on Antennas and Propagation*, 2011, vol. 59, no. 7, p. 2721–2724. DOI: 10.1109/TAP.2011.2152346
- [11] EVANS, H., GALE, P., ALJIBOURI, B., et al. Application of simulated annealing to design of serial feed sequentially rotated 2×2 antenna array. *Electronics Letters*, 2000, vol. 36, no. 24, p. 1987–1988. DOI: 10.1049/el:20001407
- [12] SEDGEECHONGARALOUYE-YEKAN, T., NASER-MOGHADASI, M., SADEGHZADEH, R.A. Broadband circularly polarized 2×2 antenna array with sequentially rotated feed network for C-band applications. *Wireless Personal Communication*, 2016, vol. 91, p. 653–660. DOI: 10.1007/s11277-016-3485-4
- [13] LI, Y., ZHANG, Z., FENG, Z. A sequential-phase feed using a circularly polarized shorted loop structure. *IEEE Transactions on Antennas and Propagation*, 2013, vol. 61, no. 3, p. 1443–1447. DOI: 10.1109/TAP.2012.2227103
- [14] DENG, C., LI, Y., ZHANG, Z. et al. A wideband sequential-phase fed circularly polarized patch array. *IEEE Transactions on Antennas and Propagation*, 2014, vol. 62, no. 7, p. 3890–3893. DOI: 10.1109/TAP.2014.2321380
- [15] FU, S., FANG, S., WANG, Z., et al. Broadband circularly polarized slot antenna array fed by asymmetric CPW for L-band applications. *IEEE Antennas and Wireless Propagation Letters*, 2009, vol. 8, p. 1014–1016. DOI: 10.1109/LAWP.2009.2031662
- [16] YANG, W., ZHOU, J., YU, Z., et al. Bandwidth- and gain-enhanced circularly polarized antenna array using sequential phase feed. *IEEE Antennas and Wireless Propagation Letters*, 2014, vol. 13, p. 1215–1218. DOI: 10.1109/LAWP.2014.2332560
- [17] MADDIO, S. A compact wideband circularly polarized antenna array for C-band applications. *IEEE Antennas and Wireless Propagation Letters*, 2015, vol. 14, p. 1081–1084. DOI: 10.1109/LAWP.2015.2392387

About the Authors ...

Saeed MOHAMMADI-ASL was born in Urmia, Iran, 1984. He received his B.Sc. and M.Sc. degrees in Electrical (Telecommunication) Engineering from Urmia University, Urmia, Iran in 2008 and 2010, respectively. His primary research interests are in antenna design, numerical methods in electromagnetic and microwave components.

Javad NOURINIA received his B.Sc. in Electrical and Electronic Engineering from Shiraz University and M.Sc. degree in Electrical and Telecommunication Engineering from the Iran University of Science and Technology, and Ph.D. degree in Electrical and Telecommunication from the University of Science and Technology, Tehran, Iran in 2000. From 2000 he was an Assistant Professor and now he is a Professor in the Dept. of Electrical Engineering, Urmia University, Iran. His primary research interests are in antenna design, numerical methods in electromagnetic, microwave circuits.

Changiz GHOBADI was born in June, 1960 in Iran. He received his B.Sc. in Electrical Engineering Electronics and M.Sc. degrees in Electrical Engineering Telecommunication from Isfahan University of Technology, Isfahan, Iran and Ph.D. degree in Electrical-Telecommunication from University of Bath, Bath, UK in 1998. From 1998 he was an Assistant Professor and now he is a Professor in the Dept. of Electrical Engineering, Urmia University, Iran. His primary research interests are in antenna design, radar and adaptive filters.

Maryam MAJIDZADEH was born in 1987 in Urmia, Iran. She received her B.Sc. in Electrical Engineering from Urmia University in 2009. Then, she received her M.Sc. and Ph.D. degrees in Communication Engineering from the same university in 2012 and 2016, respectively. She is now an Assistant Professor in Electrical Engineering Dept., Urmia Technical College, Technical and Vocational University, Urmia, Iran. Her research interests include antenna design, antenna miniaturization techniques, frequency selective surfaces, and electromagnetic compatibility.